Antineutrino Monitoring of Reactors
Theoretical Feasibility Studies

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Addressing Questions Raised at the International IAEA meeting Vienna 2003

- Can antineutrinos be used to monitor Pu content of reactor?
- Are undeclared fuel removals/diversions detectible with neutrinos?
- Are other fuels distinguishable from Lightly enriched Uranium (LEU), e.g., ^{232}Th-^{233}U
- Can neutrinos verify the burnup of MOX-Pu fuel?
- Can neutrinos determine the isotopic content of spent fuel?
- Can neutrinos detect the movement/diversion of spent fuel?

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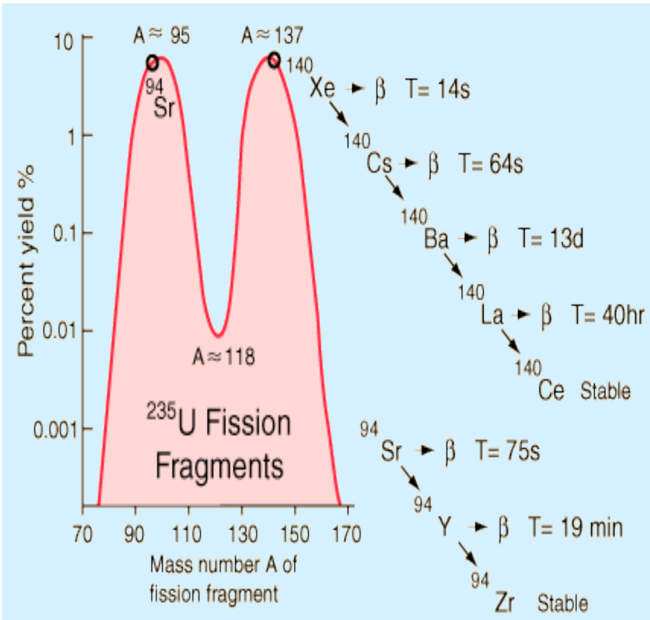
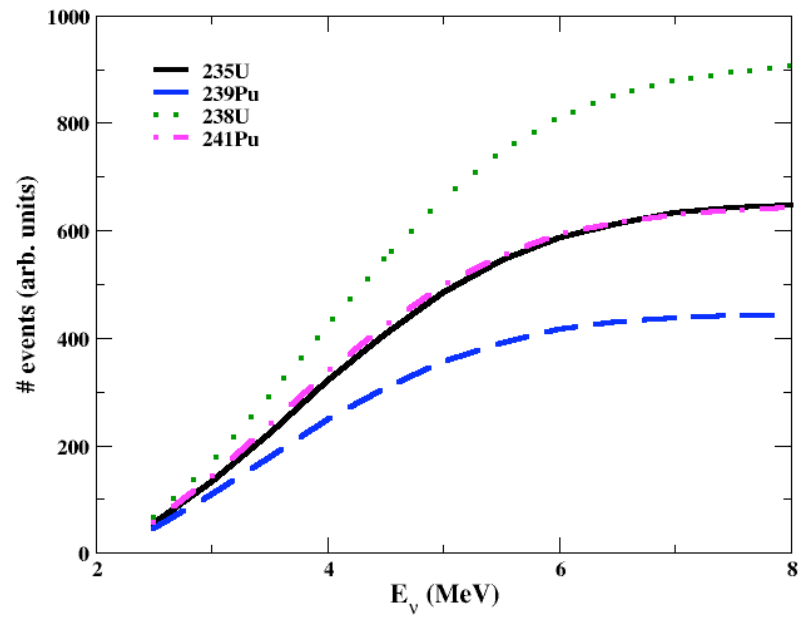
Antineutrino Spectra for Different Fissionable material distinguishable





$$N(E_\nu) = \sum Y_i(A_i,Z_i) \sum b(E^j_0)\ \ N(E_\nu,A_i,Z_i,E^j_0)\ F(E,Z)$$

Fission fragment yields
~ 300

Branching ratios
~ 10 per fragment

Fermi function

Approximately 10% of the beta decays have unknown end-point energies E_0
Use continuous theory of beta-decay or energy-independent scaling

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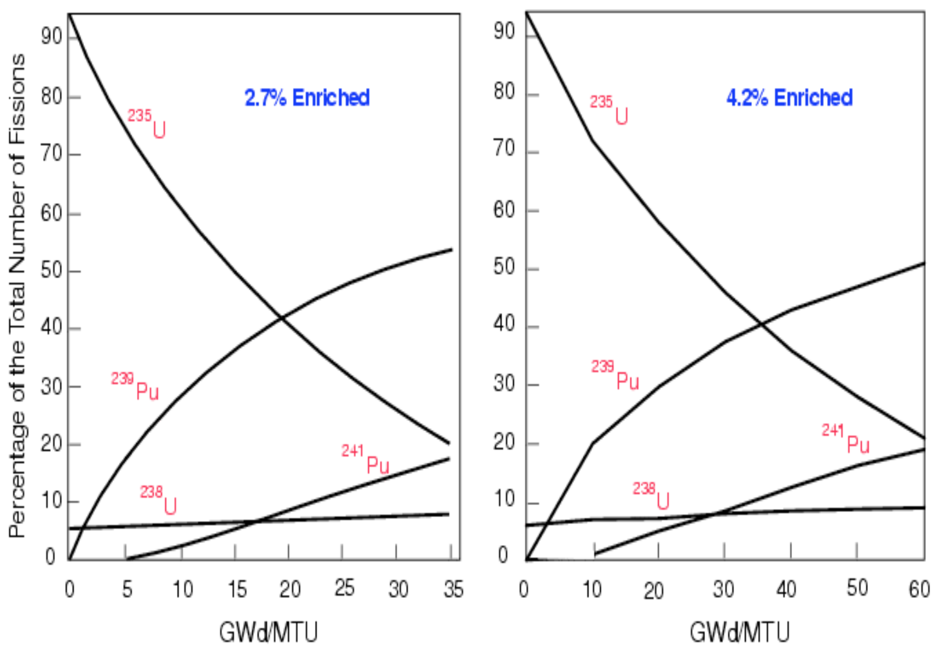
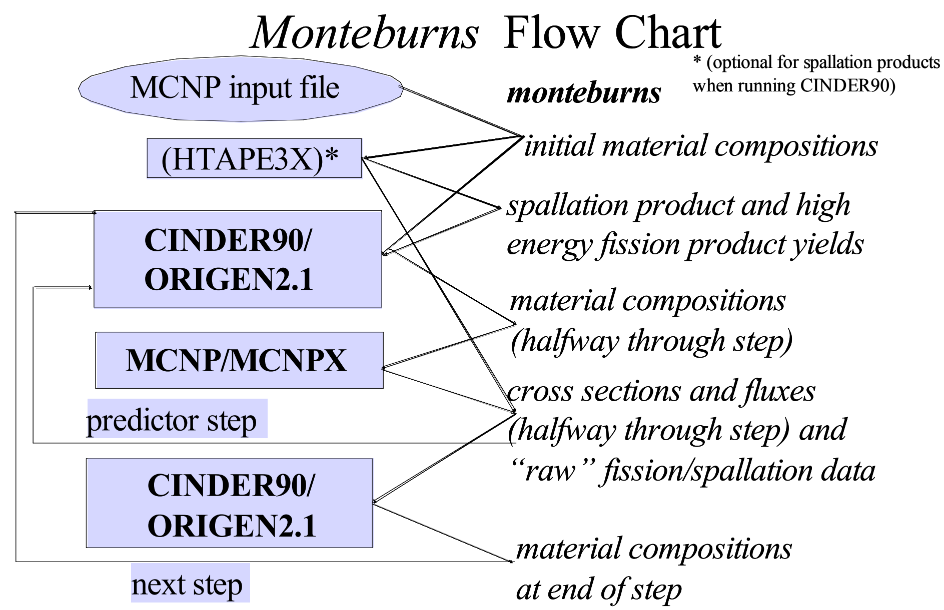
Reactor Burn Calculations using LANL code Monteburns

Monte Carlo burnup code that links MCNP transport with isotope production/depletion code CINDER'90 (or ORIGEN2.1)





- Accurate reactor modeling for a broad class of fuels.
  - Spatial and temporal power, fuel composition, radiation and decay heating
- Detailed characterization of removed fuel content and emissions.
  - Fuel proliferation index, weapons usability, decay signatures for safeguards

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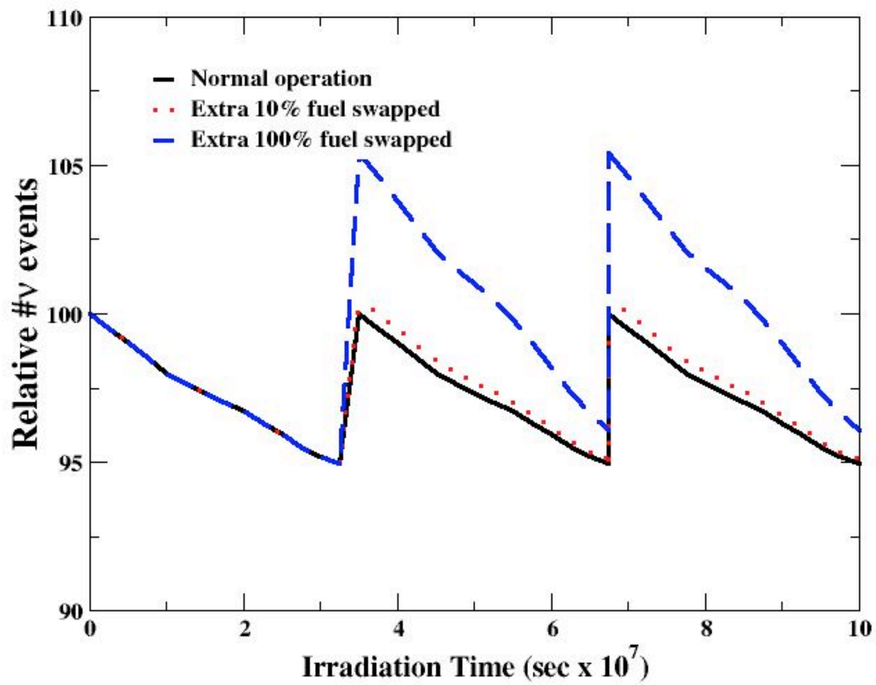
Antineutrino Spectrum for Different Fuel Diversion Scenarios

Start of cycle:
1/3 fresh 2.7% enriched
1/3 irradiated 1 year
1/3 irradiated 2 years

End of cycle:
1/3 irradiated 1 yr, 2 yr, 3 yr

Diversion of 10% (> Critical Mass):
37% fresh 2.7% enriched
33% 1 yr, 30% 2 yr

Gross Violation (diversion of 1/3):
2/3 fresh 2.7% enriched
1/3 irradiated 1 yr



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Antineutrino Monitoring of Th-U-233 reactors - Advanced Fuel cycle concept

$$^{238}U + n \rightarrow {}^{239}U \rightarrow {}^{239}Np + \beta^- + \nu \rightarrow {}^{239}Pu + \beta^- + \nu$$

$\sigma=1.73\ b$

$$^{232}Th + n \rightarrow {}^{233}Th \rightarrow {}^{233}Pa + \beta^- + \nu \rightarrow {}^{233}U + \beta^- + \nu$$

$\sigma=4.62\ b$

Advantages of Th-U fuel cycle:

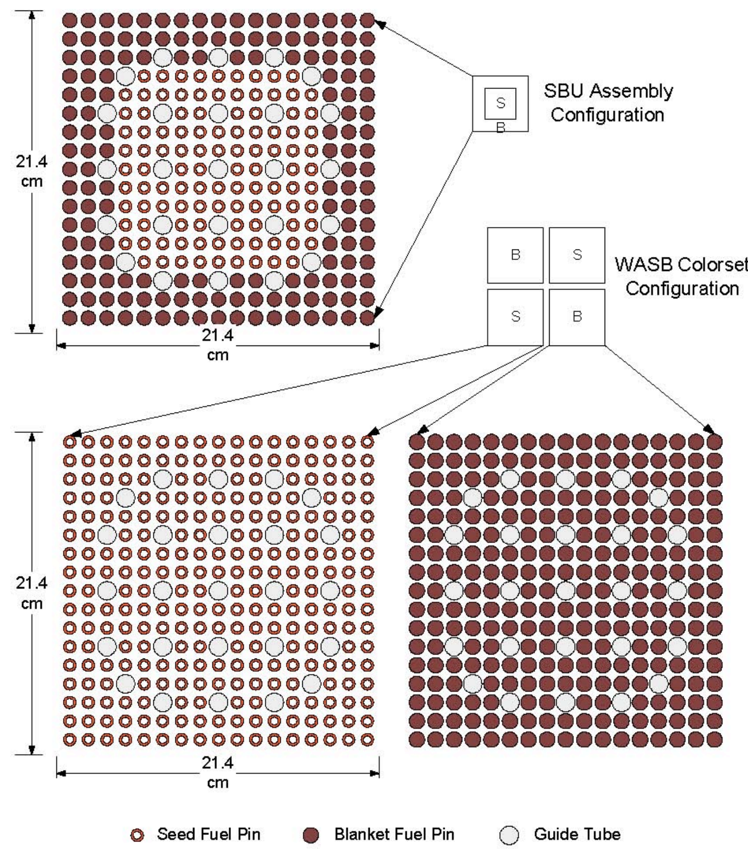
- Abundance of Th 3 times than U
- Reduced proliferation hazard
- Reduced radiological hazard

Main Disadvantage:

- Requires fissile seed (^{235}U) to initiate cycle

Seed: LEU (^{238}U + 2.7%^{235}U)

Blanket: ThO_2 or $Th0_2$ + 20% LEU



Proliferation Implications for Th-U Cycle

Weapons usability of ^{233}U determined by the proliferation index

Proliferation Index:

$$PI = \frac{^{233}U + 0.6\ ^{235}U}{U_{total}} \quad < 12\% \text{ if non-weapons usable}$$

PI typically requires about 20% of $Th0_2$ rods to contain LEU (^{238}U + 2.6% ^{235}U)

Examine antineutrino spectra differences for Th-U fuels comply/violate PI

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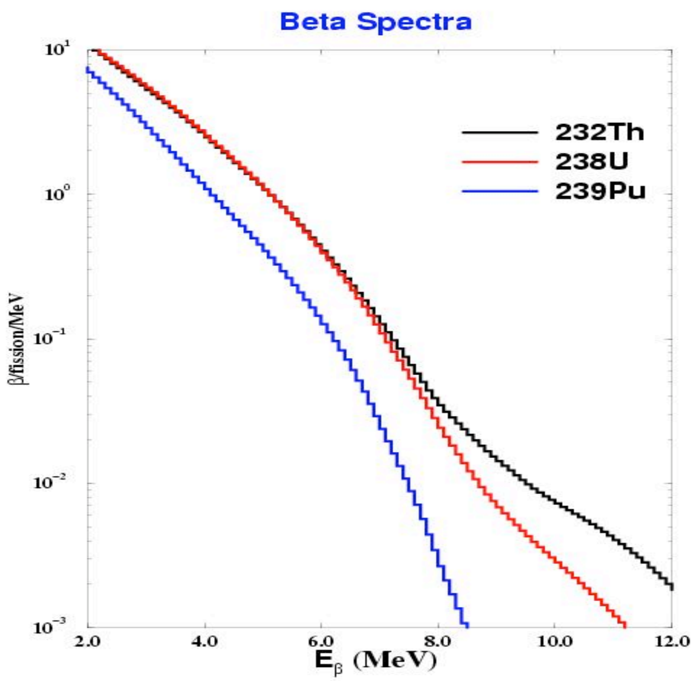
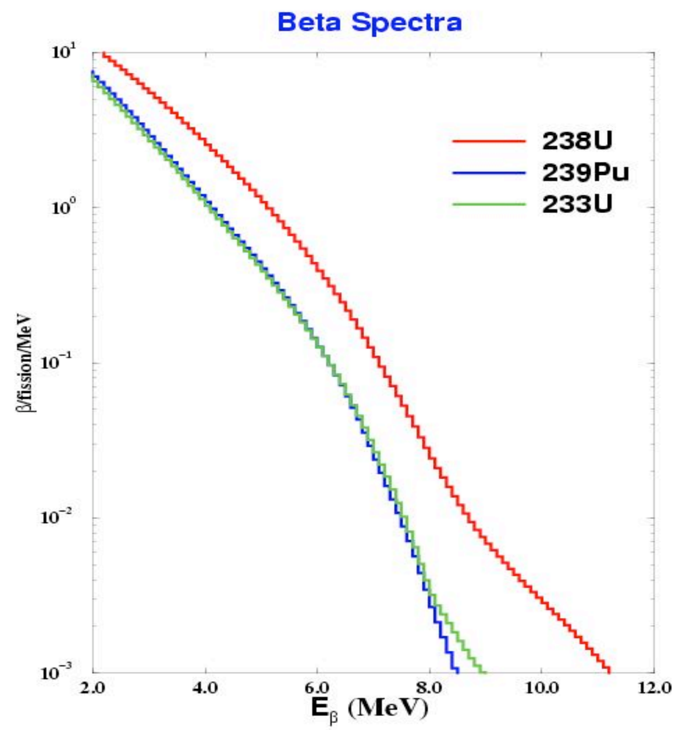
Derived β/ν spectra for ^{232}Th and ^{233}U from ENDF/B-VI data





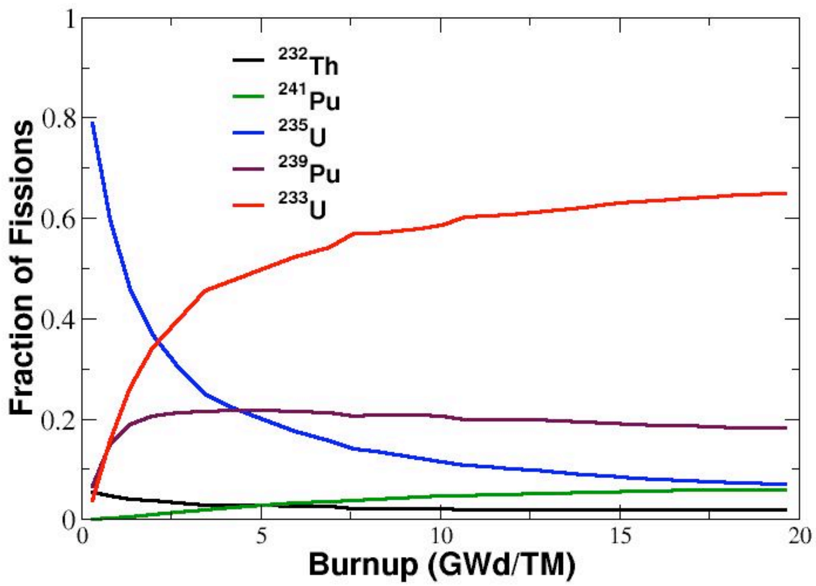
^{232}Th spectrum very similar to ^{238}U - enhanced
^{233}U spectrum very similar to ^{239}P - suppressed

Reactor Burn calculation for Th-U cycle

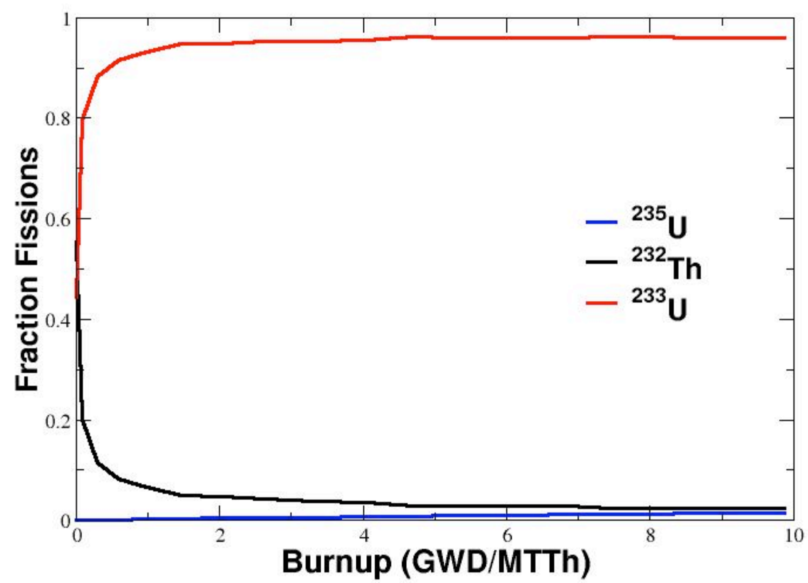
a. $Th0_2$+LEU PI compliant

b. ThO_2 to max weapons usability

a. 80%Th + 20% LEU



b. 100% Th + (small fraction 235U)



- Fast in-growth of ^{233}U in both cases, but especially for pure $Th0_2$
- Burn for the purposes of producing weapons usable ^{233}U very distinctive

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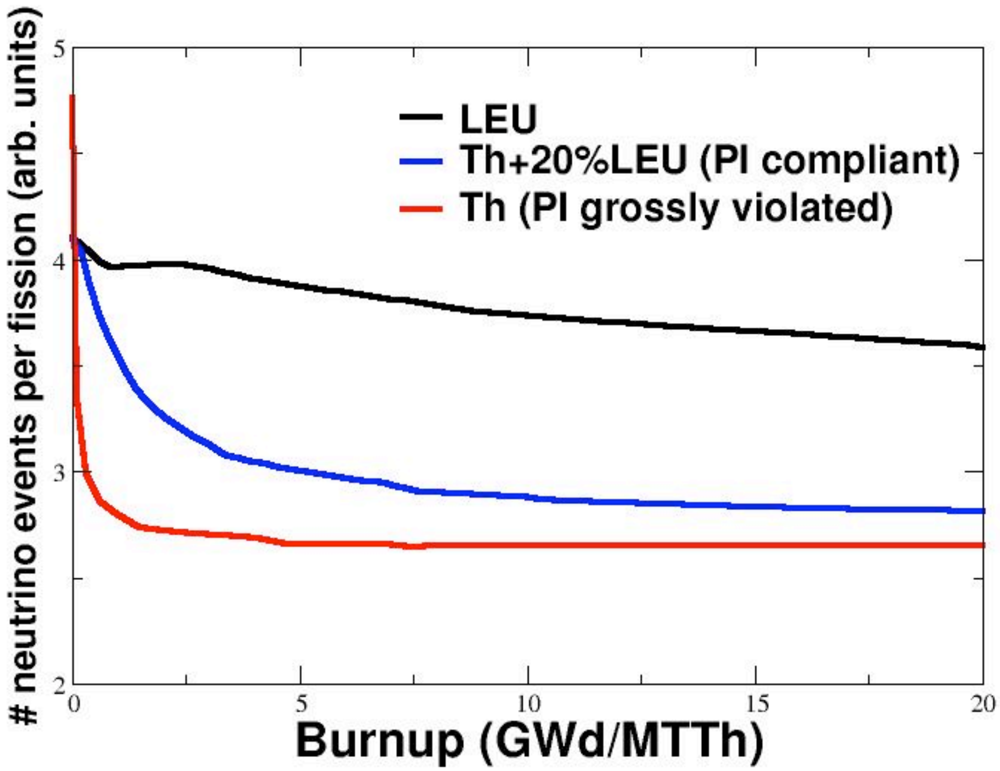
Antineutrino Spectra for Th-^{233}U cycles



Number of ν/fission drops steadily as ^{233}U grows
Considerably faster drop than seen from in-growth of Pu in PWR LEU case

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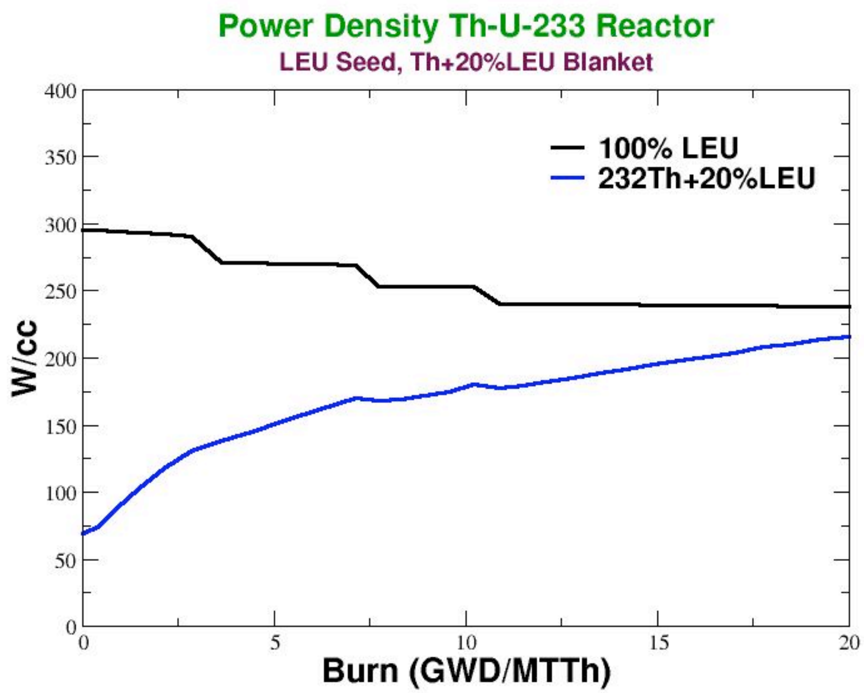
Situation Complicated by Change in Power Density for Th-U Burn

- For PWR LEU reactors power density remains approximately constant
- For Th-U reactors the power would be shared between LEU seed assemblies and Th-U blanket assemblies.
- Power in Th-U-233 assemblies can change significantly over several cycles and be compensated for by a change in the LEU power



Need detailed model of change in power density in order to determine expected change in antineutrino spectrum

Burning of Weapons-grade and Reactor-grade MOX Pu

Schemes to burn MOX fuel to burn Pu

$U0_2$ + 5.3% PuO_2

Starting Isotopics for Weapons- and Reactor-grade fuels

w%	Weapons-Grade	Reactor-Grade
U-235	0.67897%	0.67897%
U-238	93.622%	93.622%
Pu-238	-	0.2026%
Pu-239	5.0%	2.6527%
Pu-240	0.3%	1.373%
Pu-241	-	0.5345%
Pu-242	-	0.5372%

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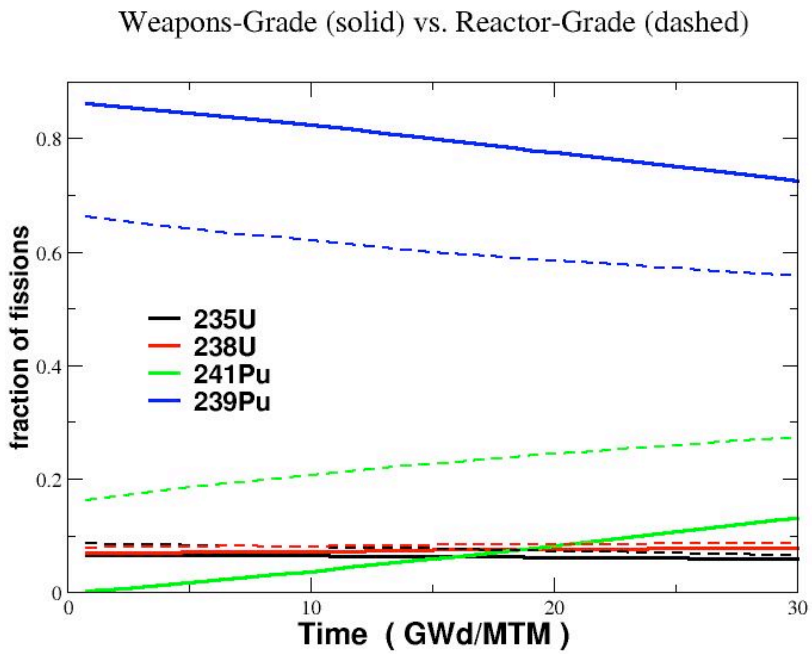
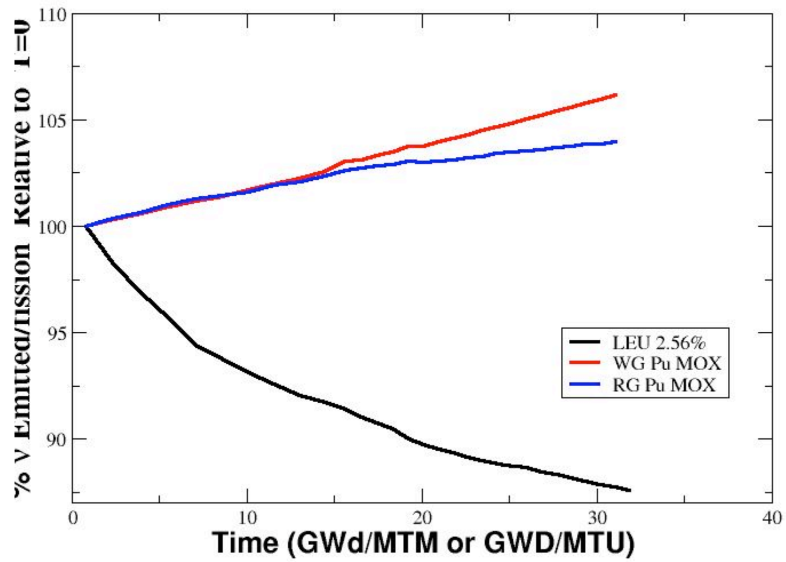
Antineutrino Spectra Emitted for Pu MOX Fuels Clearly Distinguishable

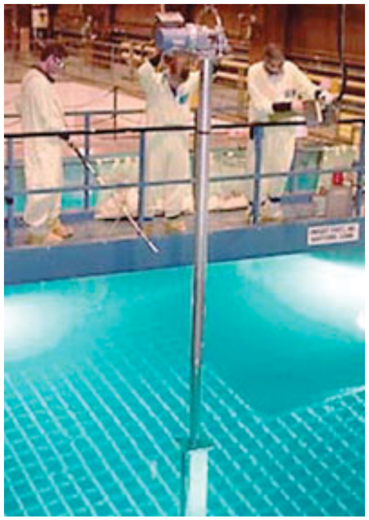




Number Antineutrinos/fission ***increase*** with burn for MOX PU

May be able to distinguish grade of fuel from power density

Monitoring Spent Fuel



The antineutrino source describes total activity well

-essentially all decays are β-decay.

Calculated activity of discharged fuel drops to:

7.5% in the 4 weeks

1.5% in a year

0.2% in 10 years

Fuel assembly would have to be moved far from reactor

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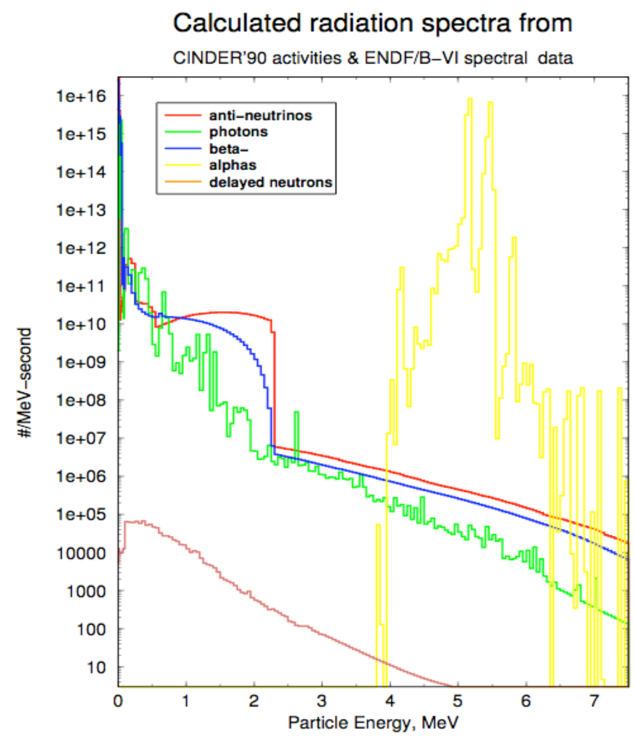
Radioactivity at WIPP
Carlsbad, NM

WIPP designed to store ~ 9000 Mtonnes
of radioactive waste

Presently 25% full

Radioactivity includes
Antineutrinos
Betas
Delayed photons
Alphas
Delayed neutrons



WIPP antineutrino and beta spectra
Dominated by 241Pu 18 keV β-decay

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Summary

- For LEU PWR gross changes in fuel content likely to be observable
- Diversions of a critical mass of Pu from GW LEU PWR difficult to detect
- Th-U233 fuels distinguishable from LEU
- Violations of the proliferation index for Th-U233 quite distinguishable.- important for monitoring the proposed Indian breeder reactor program.
- Burning of MOX Pu fuels also distinguishable
- Antineutrino spectrum from spent fuel peaks at very low energies

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